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VOLCANOS AND RADIOACTIVITY[1]

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One of the commonest, and perhaps the most impressive, of natural phenomena, the volcano, has hitherto been without any explanation of its cause, though it has been before the world a subject of theory for many centuries. The reason for this is quite apparent. We perceive the action of the volcano upon the surface, and we know what it does. But the theater of its origin and the development of its energy are far below the surface of the ground, out of reach of inspection or direct observation. Human ingenuity has been baffled in its efforts to explain the phenomenon because of the want of observed facts and the impossibility of obtaining them. But, while we are, and probably always shall be, unable to directly inspect the seat of origin of the volcanos, there are certain inferences in connection with them which have attained a degree of probability which entitles us to use them as facts which may limit speculation and confine it within very narrow boundaries. I purpose to mention these inferences in order to see the general nature of the solution to which they point; for, unless I am greatly mistaken, they will show us that we are close upon the verge of a solution.

1. The first fact to be mentioned is the solidity of the earth. It is so well known that I shall not dwell upon it, and merely mention it in order to bring it, together with other facts, into the same series or group.

[1] Read before the National Academy of Sciences, April 17, 1906.

2. The second fact is the comparative smallness of the extravasated masses in any single volcanic eruption. In order to obtain an idea of the relative magnitude of an erupted mass, let us draw upon a true scale, a segment of 1° of the earth's surface, of an arbitrary thickness—say thirty miles. Upon this segment draw the profile of Vesuvius. About a mile below the surface, beneath the volcano, draw the reservoir of lava, having the same mass as the volcano itself. It may have any thickness and any form, and is subject only to the condition that the capacity of it is the same as the mass of the erupted material. Now, Vesuvius is built of I know not how many individual eruptions, but let us say one hundred; though I presume that there were, in reality, very many more. A single average eruption would be the hundredth part of the volume of this reservoir. But there are eruptions known which are many times greater than the average of those of Vesuvius. The largest known in the United States are in the Snake River valley, and while we are not in a position to compute with accuracy their dimensions, we can say with confidence that the volume of the largest of them does not exceed two cubic miles. The great eruption of the Skaptar Jökul, in Iceland, in the year 1783, was estimated by Dr. Thoroddson to have outpoured twelve or thirteen cubic kilometers, or three cubic miles of lava. The greatest eruption of which we have any estimate—and that is a very crude one—was at Tomboro, on the island of Sumbawa, which was estimated to have discharged about six cubic miles of lava. This estimate is very excessive, and is probably two or three times too large.

On the same scale as before these two eruptions are represented, and you perceive how insignificant they are in mass in comparison with the whole of the surrounding earth.

3. The third general fact is the repetitive nature of volcanic eruptions. A single outbreak, with none following, is an exceeding rare phenomenon. Many eruptions, going often into the thousands, occur before the climax is reached and the decline of activity follows. The reason why a volcano, when its vent is once open, does not discharge all the material in its reservoir in one stupendous belch, and then close up forever, will be shortly brought up.

4. The next general fact, which we cannot claim to be proven, but

for which there is a growing mass of strong and highly concordant evidence, is that the seat of the reservoir is very shallow and seldom more than three miles deep. Very rarely is there any indication of its being more than two and one-half miles deep, and it is certain that in many cases the depth is less than one mile. The indications are that most of the volcanic eruptions originate at depths between one mile and two and one-half miles. The evidence of this is furnished by the earthquakes which almost always accompany them, and which are associated with them in such a way as to leave no doubt or question that they are produced by the volcanic action. The radiation of the tremors of an earthquake from their source in the earth is governed by substantially the same law as sound. The intensity of these tremors, where they reach the earth's surface, varies in a manner which is dependent upon their depth of origin. In the discussion of the Charleston earthquake I pointed out one method by which that depth can be approximately computed from the distribution of critical points of the surface intensity. The method has been sharply criticized by able seismologists as being liable to error through refraction of the rays of propagation through rocks and media of variable density. But I observe that all of them use that method with surprising consistency and satisfactory results.

The efficiency of this method depends mainly upon the accuracy with which the intensity can be estimated along a line radiating from the epicentrum. It often happens that the intensity is so much affected by the local nature of the soil and rocks that all estimates become so uncertain as to be very misleading, and all attempts to draw conclusions from them must be affected by large errors, or may fail entirely. On the other hand, in many cases the results are safer and surer than would be supposed, and we are able to give a graphic representation of the curve of intensity which must be very near the truth. In general, when an earthquake is very strong at the epicenter and quickly fades out away from it, we can say with confidence that its centrum is very shallow. If the intensity fades out slowly and the quake is felt at great distances, we can rely upon its centrum being very deep. When, therefore, we have not the means of estimating the intensity at the critical points, if we have the means of estimating the maximum intensity of the quake and of knowing how far it is felt, we can still form,

not indeed a precise or accurate estimate of its depth, but a roughly approximate one.

A qualification of the foregoing may be introduced here. The earthquake is no doubt the fracturing or sudden yielding of the rock masses immediately above the lava reservoir. We can only vaguely conjecture the distance which separates the zone of fracture from the zone of melting. But in no case could it be so great as a mile without making itself sensible in the greater depth of the quake. We must, however, increase slightly our estimate of the depth of the lava beyond the estimated depth of the quake.

We may now proceed to state the probable cause of volcanic eruptions. They are caused, I conceive, by a development of heat, resulting from radioactivity, in limited tracts at a depth of one to three —at the very utmost not over four—miles from the surface, which is sometimes sufficient to melt the rocks affected by it. The melting is gradual, and when a sufficient quantity is melted, the water which it contains becomes explosive and usually suffices to break through the covering, constituting an eruption. When all the lava is erupted, and the reservoir is exhausted, it closes up for a time. If the heat continues to be generated, more lava is melted, and in due time another eruption occurs. The process may be repeated again. It may be repeated hundreds or thousands of times. The volcanic action may continue in the same place for hundreds of thousands, or even millions, of years, or it may repeat itself only a few times, or may even occur only once. Indeed, it may fail altogether to erupt to the surface, and in many cases does fail. In other words, it goes through the entire process of preparing for an eruption and does not consummate it.

This view enables us to explain the repetitive character of volcanic eruptions, which is, perhaps, their most striking and characteristic feature. It is in strong contrast with the view long held that the lava reservoirs are a part of the original constitution of the earth, and have lain in their present position through all the vast period of the earth's evolution, waiting for a convenient occasion to explode and pour forth their fiery contents. It regards the reservoirs as having no real existence as such, and as containing no liquid eruptible contents until some source of heat acts upon them and liquefies a portion of the strata, thus giving rise to the reservoir. When a sufficient quantity of the lava is

melted to rupture its covering, the eruption follows. It continues until all the lava which exists for the time being in the reservoir is extravasated. . And when all of its ammunition is expended, it must close its action until a fresh supply is provided.

By an increase of heat, we can readily understand the existence of the lava reservoirs in such anomalous positions near the surface of the earth. The horizon of melted lava, which has a temperature of about 1,000° or 1,200° C., if it depended wholly upon the secular cooling of the earth would be more than thirty miles below the surface, or even forty miles below. We cannot suppose that the cooling of the earth is so extremely unequal as to bring the isotherm of 1,000° C. at one place within two miles of the surface, and in another place carry it thirty or forty miles below. It is equally difficult to imagine any subterranean disturbance or displacement which could mechanically thrust up near the surface a portion of the solid nucleus of the earth. Such a displacement is not warranted by the geological facts; for while volcanic eruptions occur frequently in localities where the strata are much displaced, they also occur quite as often where there has been no displacement of any moment since the Cambrian age.

A singular class of phenomena is found in the so-called mud volcanos, which have always been a great puzzle, but which are easily explained by this cause. We find them in Central America and in Java, and the remarkable case of Bandai San, in Japan, is well remembered. These volcanos must have their origin at less depth than the lava eruptions. The temperature of erupted mud is not accurately known, but it cannot be less than 400° or 500° F. The generation of heat half a mile below the surface would be a sufficient explanation of their origin and action.

Why should eruptions always emanate from shallow reservoirs and never from deeper ones? Or, according to the view here put forth, why are eruptive masses formed only at depths of two or three miles, and never at greater depths? I do not contend that no lava pools are formed at greater depths than three or four miles, but if they are formed, the lava is never erupted, and for the following reason. The pressure of the overlying rock at a depth of three miles is about 18,000 pounds to the square inch. At a depth of four miles it is about 25,000 pounds to the square inch. At such a pressure (25,000 pounds) it would be im-

possible for water vapor to lift its covering and force a way to the surface, unless it had a temperature greatly exceeding 1,200° C. It would have to be heated to a considerably higher temperature to do it. But with increasing temperature the heat is conducted away more and more rapidly, until the loss of heat is equal to the quantity generated and thereafter there is no increase of temperature. The generation of radioactive heat is a slow process, and the only method of its escape is by conduction away from the radioactive source. The rate of heat generation is constant and independent of the temperature, but the rate of loss increases rapidly with the temperature. Ultimately, as the temperature rises, a point would be reached at which the loss of heat becomes equal to the gain.

If an eruption from a deep source, say five or six miles, were to occur, we should expect that the temperature of the lava would be very high—probably a white heat—and that its mass would be very great. Its consequences might be disastrous beyond all precedent.

That volcanism is caused by the generation of heat near the surface was a belief which I expressed over twenty years ago in a chapter of the work on *Hawaiian Volcanos*. Long study of the volcanic problem, in which every other theory failed and went to pieces under criticism, and this alone not only survived, but grew more probable and in accordance with the facts, led me to the hazardous step of venturing to express it. At that time no cause could be cited for the increase of heat, and the proposition met with no response—and, no doubt, justly. Geologists continued to look for the explanation of volcanoes in the gradually waning remnants of the earth's internal heat. Within the last five or six years, however, physical science has made discoveries of a wonderful nature, which open a new field—indeed, a new world—in our views of the constitution of matter, and may throw a flood of light on the very subject of our inquiry.

The subject of radioactivity is so new and so surprising that it has had time only to establish a very few of the fundamental principles which lie at the basis of it. But so hotly is the matter pursued by many of the ablest specialists that each year shows a large increase in our knowledge. As this is familiar to all physicists, I shall allude here briefly only to such as are essential to our discussion. We have to regret that some of the most fundamental questions concerning radio-

activity are as yet unsolved, though we cannot expect that a new and and far-reaching science should in six years have accomplished all of its immense possibilities.

A good many efforts have been made, by the use of the extremely sensitive quadrant electrometer, to ascertain by measurement the quantity of radioactive substances in the accessible portions of the earth. By taking samples of earth from varying depths and testing them by the electrometer, widely variable quantitative results have been obtained, but in every instance the amount of radioactivity indicated much exceeds the amount required to compensate the loss of heat from the earth by conduction and radiation into space. For instance, Professors Elster and Geitel, of Berlin, who have made many discoveries and contributed many observations in radioactivity, placed 3,300 ^{cc} of garden soil within a closed vessel with an electroscope to determine the conductivity of the inclosed gas. Allowing it to stand for several days, the conductivity of the air became constant at three times the normal amount. This increase of conductivity, Professor Rutherford estimates, would be equivalent to that produced by the emanation from 7×10^{-10} grams of radium. If the density of the soil be taken as 2, this corresponds to the emanation from 10^{-13} grams of radium per gram of clay. Now, Professor Rutherford computes that the earth's loss of heat by conduction and radiation is equivalent to what would be supplied by 4.1×10^{-14} grams of radium per cubic centimeter of its mass. According, then, to the results obtained by Elster and Geitel, twice as much heat would be supplied by radioactivity as is lost by conduction and radiation into space.

This experiment with a small quantity of soil taken up in somebody's back-yard will hardly be regarded as an accurate determination of such a quantity as the earth's supply of radioactive heat. But the question has been tested by many observers, whose results vary considerably, yet all are of the same order of magnitude. By sinking a pipe into the ground anywhere, and sucking up a sample of the air from the soil, it is found to possess a much higher degree of radioactivity than the free air at the surface. It also has a marked degree of conductivity; and this conductivity falls to half of its initial value in a little less than four days, which is regarded as proving that it is due to radium emanation. The air of caves and cellars has been observed to have a marked degree

of ionization, greatly exceeding the open atmosphere and the air in closed vessels. This is attributable only to the presence of radium emanation diffused from surrounding rocks or soils. Many common well waters give satisfactory tests of the presence of radium emanation, which is soluble in water—more so than most gases.

The most pronounced occurrence of radium is in hot springs. Their waters always give evidence of its presence, and sometimes in quantities many times exceeding the air taken from the soil or cellars. Hon. R. J. Strutt, of Trinity College, has devoted much attention to the Springs of Bath, and finds not only radium emanation in their waters, but actual radium in the deposits of the springs. The hot springs of Baden Baden have been found to contain radium salts. M. Curie has tested a large number of the mineral springs of central and southern France, and finds radium emanation in nearly all of them. Mr. Boltwood, of New Haven, has devoted considerable attention to the study of radioactivity in mineral springs, and finds that many of the waters of America contain radium emanation.

It does not appear that any extensive or systematic investigation of the emanations of active volcanoes and volcanic gases has been made. The only one I can discover is the observation of Rausch von Trauenburg on the crater of Vesuvius. The gases from that orifice produced marked ionization and a prompt discharge of the leaves of the electroscope. The subject, however, needs thorough investigation at many other volcanic vents.

The general result of the investigation, so far as it has gone, has been to make clear the fact that the amount of radioactivity in the earth much exceeds the amount which is necessary, so far as the heat generated by it is concerned, to compensate the loss of heat by conduction and radiation. In fact, it appears that the thermal condition at present is one of continual increase of internal temperature of a large portion of the earth, or is so in part, or else is one of equilibrium between loss and gain. Undoubtedly the amount of radioaction varies somewhat widely in different portions of the earth's interior, in some portions permitting a loss of heat, in others permitting a gain. And when there is a gain, it may proceed in the portions near the surface so far as to liquefy the rocks, and thus furnish all the conditions necessary to volcanic eruptions.

One of the problems at present unsolved is: Whence comes this radioactive material, and what maintains its activity? For the most part, it gives us the characteristics of radium, and in smaller degree those of thorium and uranium. The action of actinium has not yet been sufficiently pronounced to be recognized. Polonium is believed to be one of the transitional forms of radium. No other radioactive substances are yet known. The most important one thus far identified is radium. But the life and activity of radium are, from a geological standpoint, very brief. According to Professor Rutherford —and he is sustained by nearly all other physicists—radium is half consumed in a period of 1,300 years. In 13,000 years only the thousandth part of what now exists will be left, and in 26,000 years only the millionth part will remain. Quite independently of geological reasons, the belief has been that radium is generated as the product of decay of some other element, and that the amount of it in nature is sensibly constant. It is generated as rapidly as it decays. The parent element from which it may be derived is not yet decided, but there are some who suspect it to be uranium, which has immensely long life. It requires nearly 120,000,000 years to be half consumed by its own decay.

But we are not interested in pursuing and trying to test these unsolved problems. It is enough for us that radioaction exists in sufficient quantity and intensity to furnish heat enough to meet the wants of the vulcanologist.

Let us now look for a moment at the presumable details of the process. At a depth of two or three miles in the earth let us assume that radium is in process of being generated. It starts at once upon that process of transfomation of which one stage is the production of the so-called emanation, which is a gas of very high density and great penetrating power and diffusability. We know that the upper strata and soils everywhere contain it, and no reason appears why the same should not be the case with the rock beneath. Wherever the emanation penetrates, the breakup of its particles generates heat, and the temperature rises in proportion to the amount of emanation which undergoes transformation in a given time, and falls in proportion to the rate at which it is conducted away. So long as the gain of heat exceeds the loss, so long will the temperature rise until it becomes sufficient to melt the rocks.

All volcanic lavas contain water, and those whose reservoirs are near the surface contain a large amount of it Those which have a deeper origin contain a smaller amount of it. The deeper lavas are hotter, and are erupted with less violence and in greater mass, than the shallow ones, and the reason is obvious.

The foregoing is a brief abstract of a portion of a book now in preparation on volcanism.